REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Feb 8, 2009	Final Report 11/15/04 - 11/14/08

4. TITLE AND SUBTITLE **Cooperative Wall-climbing Robots in 3-D Environments for Surveillance and Target Tracking**	5. FUNDING NUMBERS W911NF-05-1-0011
6. AUTHOR(S) Dr. Jizhong Xiao and Dr. Zhigang Zhu	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) CUNY City College, Convent Ave. and 138th Street, New York, NY 10031	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

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12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	.

13. ABSTRACT (Maximum 200 words)

In the final reporting period, we have produced several variant wall-climbing robot prototypes for building inspection and window cleaning tasks. We also conducted theoretical research on multi-robot coordination, swarming robotics, and 3D map construction in constrained 3D space involving City-Climber robots**.** We have developed a 3D simulation software and conducted real experiments to verify the theoretical results. We are negotiating with Hasbro Inc. for licensing the City-Climber technology in toy industry through CUNY technology commercialization office.

14. SUBJECT TERMS Wall-climbing robots, computer vision, surveillance, target tracking, 3D map construction, robot localization, swarm robotics	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

THE CITY COLLEGE
OF
THE CITY UNIVERSITY OF NEW YORK

Cooperative Wall-climbing Robots in 3D Environments for Surveillance and Target Tracking

FINAL PROGRESS REPORT

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DATE OF REPORT: FEB 8, 2009

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Forward

The objective of this project is to develop modular, reconfigurable, wall-climbing robotic systems and to investigate intelligent control methods and vision algorithms to control and coordinate a team of such robots to perform various defense, security, and inspection missions.

We have made significant accomplishments in developing novel wall-climbing robot prototypes, in theoretical analysis of multi-robot control and coordination in 3D space, and in computer vision research for sensor network, surveillance and inspection. The success of this project has taken us a few steps closer to realizing the dream of transforming the present 2D world of mobile rovers into a new 3D universe.

This final progress report summarizes the major technical achievements of the project.

List of Figures

Statement of the Problem Studied

Most of the mobile robots nowadays essentially move on the ground without wall-climbing capability. It has been a long-time dream to develop a miniature climbing robot with the ability to climb walls, walk on ceilings, and make wall-to-wall transitions, thus transforming the present 2D world of mobile rovers into a new 3D universe.

1) One of the most important tasks for the climbing robot project is to design a proper adhesive mechanism to ensure that the robot sticks to various wall surfaces reliably without sacrificing mobility. Traditional climbing robots use magnetic devices or vacuum suction can only operate on ferrous surfaces or smooth and nonporous surfaces. These constraints greatly limit the applications in real urban environments. In recent years, some novel wall-climbing robots have been developed such as the robots inspired by the gecko foot and the wall-climbing robots using vortex technology. Vortex climber is based on a so-called "tornado in a cup" technology, which allows the robot to travel on both smooth and rough surfaces. However, the adhesion force generated by the vortex is not enough to support large payload and it is difficult for the robot to make wall-to-ceiling transitions. For the gecko-inspired climbing robots, it is a challenging work to synthesize dry adhesive material strong enough for practical use, and design self-clean solution of the synthetic gecko foot-hair for operating in dirty area without loss adhesion.

We have investigated several design alternatives and developed a novel adhesion mechanism based on aerodynamic attraction which takes advantage of the merits of both vacuum suction and vortex technology and makes good balance between strong adhesion force and high mobility. We have produced four generations of robot prototypes, named as City-Climbers, which don't require perfect sealing and can operate on virtually any kinds of surfaces and achieve the largest payload capacity comparing with other wall-climbing robots with similar form factor.

2) Employing City-Climbers in a robot team in urban operations — move on the ground, on walls, and even on ceilings, provides both opportunities and challenges. One of the benefits is that the climbing robots can take vantage positions on a ceiling or wall to gain better views of a scene, and to avoid occlusions and obstacles. The challenges lie in the fact that many methods and algorithms on planning and control of multi-robot systems are no longer valid for the application scenario involving wall-climbing robots. Since the City-Climber essentially operate in 3D constrained space (i.e., its action space is confined within piecewise planar surfaces while the sensing space is 3D, facilitated by the freedom of motion on ground, walls, and ceilings), it requires optimal strategies to control and coordinate the robot actions individually as well as collaboratively to achieve a common goal (e.g., self-deployment, dynamic view planning, and target tracking, etc.).

This has motivated us to conduct basic research on multi-robot control and coordination, 3D localization and mapping, dynamic 3D scene modeling and representation, and computer vision research for surveillance and inspection.

Summary of the Most Important Results

This project has made significant achievements in terms of developing novel wall-climbing robot prototypes, theoretical analysis of multi-robot control and coordination in 3D space, and computer vision research for surveillance and inspection. We summarize the most important results in the following sections.

A. Prototypes of City-Climber Robots

We have developed 4 **generations** of wall-climbing robot prototypes, named as **City-Climbers**, which overcome the limitations of existing wall-climbing robot technologies. The City-Climber robots use aerodynamic attraction which achieves good balance between strong adhesion force and high mobility. It can move on both smooth and rough surfaces and can carry reasonably large payload (4.2kg/10lb). The capabilities of the City-Climbers are recognized by robotics research community as well as general public. The video entitled "City-Climber: a new generation of wall-climbing robot" is one of the three **finalists for the BEST VIDEO AWARD** in the Int. Conf. on Robotics and Automation (ICRA'2006). The video "City-Climbers at Work" showing the latest progress of the project was presented at the ICRA'2007, Rome, Italy, and Dr. Xiao was interviewed by German National Radio, and Swiss TV in the conference. The City-Climber robots were featured on MSNBC Newsweek, Discovery Channel website, Popular Science magazine, etc. (The videos are downloadable from CCNY Robotics Lab website http://robotics.ccny.cuny.edu).

Figure 1 a) shows the exploded view of the City-Climber prototype-I that consists of the vacuum rotor package, an isolation rim, a vacuum chamber with flexible bristle skirt seal, and internal 3-wheeled drive. Figure 1 b) shows a City-Climber prototype-I operating on real brick wall.

Fig.1 a) Exploded view of City-Climber prototype-I; b) City-Climber prototype-I approaching a window on real brick wall, a CMU-camera is installed on a pan-tilt structure for inspection purposes

The City-Climber prototype-II adopts the modular design and introduces a hinge assembly for smooth wall-to-wall transition. Each module can operate independently and is designed as triangle shape to reduce the torque needed by the hinge assembly to lift up the other module. Figure 2 a) shows the City-Climber prototype-II resting on a ceiling and Figure 2 b) and c) show a conceptual drawing of two City-Climber modules operating in gang mode that allow the unit to make wall-to-wall and wall-to-ceiling transitions.

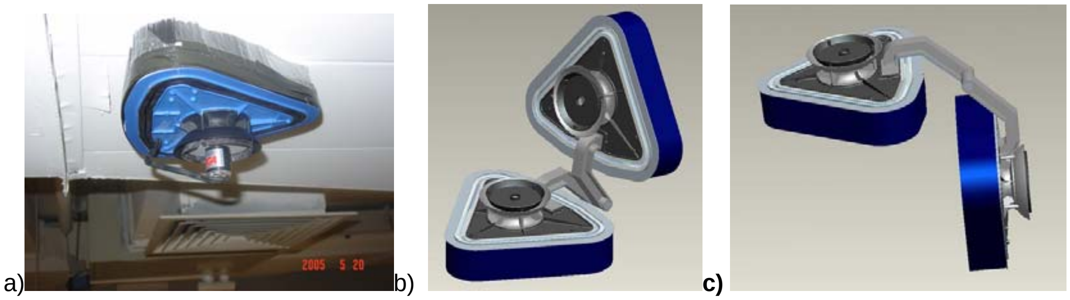


Fig. 2 a) The City-Climber prototype-II rests on a ceiling; b) and c) Two climbing robot modules connecting by a hinge in +90°, and -90° configurations, being able to make wall-to-wall, and wall-to-ceiling transitions.

The City-climber prototype-III adopts 6-wheel driving system to increase the contact friction while climbing vertical walls. The City-climber prototype-IV is a two-module version with closely coupled hinge mechanism. Each module can operate independently and can make ground-to-wall transition with ease. The two modules are closely coupled to reduce the torque required to lift up other module, as shown in Fig. 3. Due to efficient placement of the driving system the robot is capable of +/- 90 degree transitions, improved the performance of City-Climber prototype-II. Additional multiple modules could be linked together to form a snake-like version. The technical details are presented in the papers [1~3, 6, 8~9, 16].

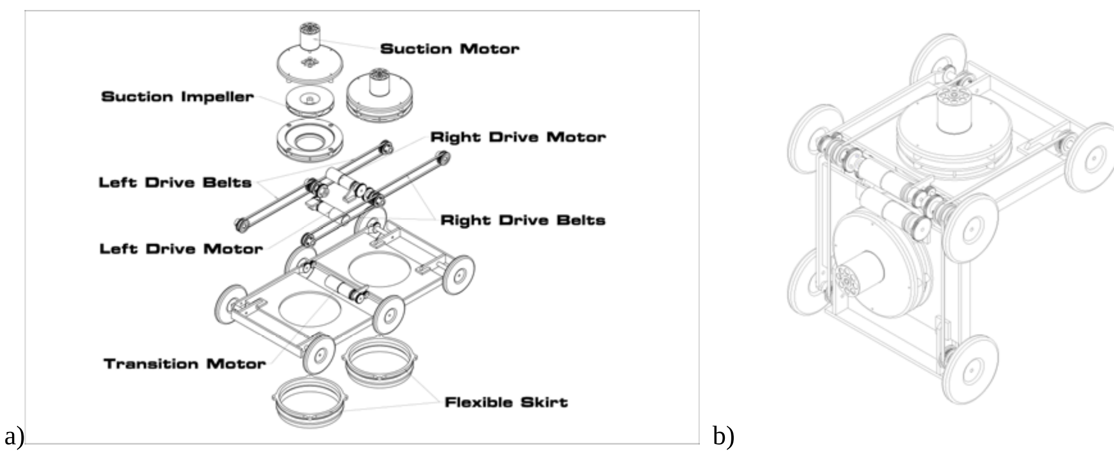


Fig. 3. a) Exploded view of City-Climber prototype-IV, two modules are closely coupled with one transition motor placed in the middle and two other motors drive the two center wheels (left and right), and via the driving belts drive the front and rear wheels. b) Conceptual drawing of City-Climber prototype-IV in 90 degree configuration

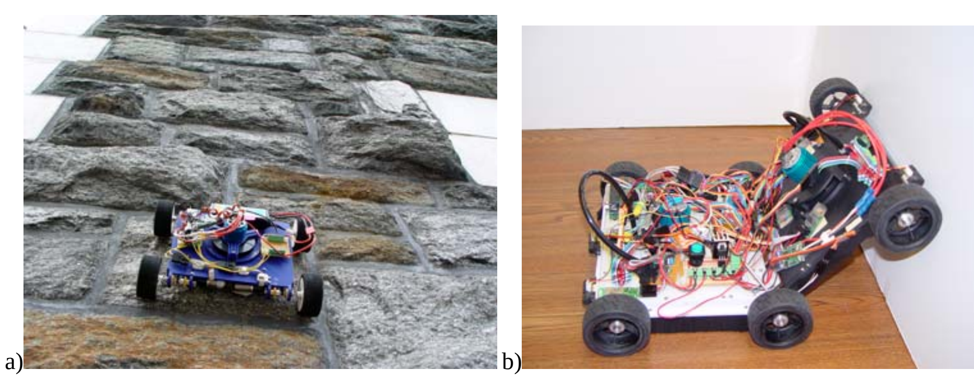


Fig. 4. a) One module City-Climber prototype-III resting on a brick wall; b) two module City-Climber prototype-IV making ground-to-wall transition

In addition, we have developed some variant wall-climbing robot prototypes for building inspection and window cleaning tasks. We are negotiating with Hasbro Inc. for licensing the technology in toy industry through CUNY technology commercialization office.

B. Aerodynamic Analysis

Unlike the traditional climbing robots using magnetic devices and vacuum suction techniques, and some recent novel climbing robots of vortex climber and the robots inspired by the gecko foot, the City-Climber robots use aerodynamic attraction produced by a vacuum rotor package, which generates a low pressure zone enclosed by a chamber. Since the City-Climber robots don’t require perfect sealing as the vacuum suction technique does, the robots can move on various smooth or rough surfaces, such as brick walls, concrete, wood, glass, stucco, plaster, gypsum board, metal, etc.

We studied the aerodynamic behavior of the adhesion mechanism of the City-Climber robots by means of computational fluid dynamics (CFD) simulation using Fluent software. The simulation results reveal that the aerodynamic attraction is affected by many factors, such as the impeller speed, shape and distribution of impeller vanes, volume of the chamber, and sealing effect, etc. Fig. 5 and 6 show some exemplary simulation results. In paper [11], we presented the aerodynamic analysis which matches the experimental results and provides directions to improve the adhesion mechanism. The current design has achieved largest attraction force comparing with other wall-climbing robots with similar form factor.

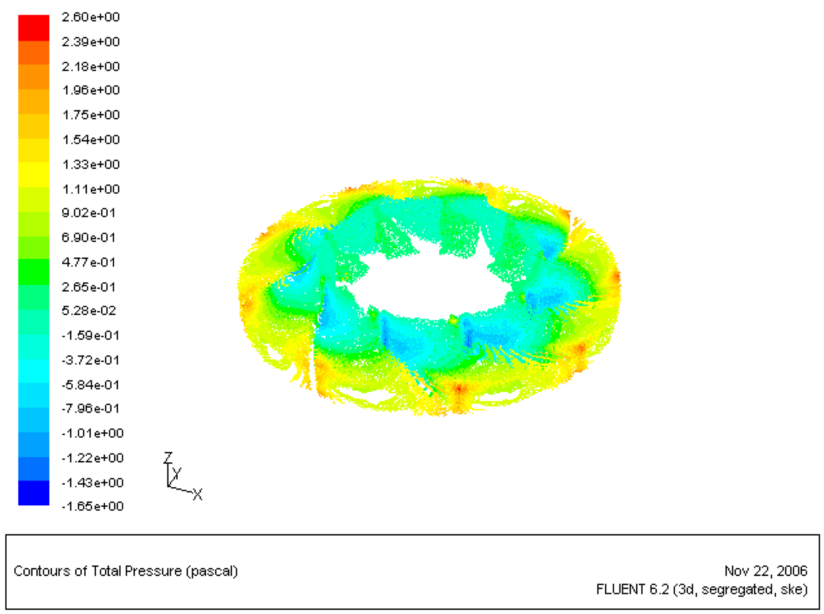


Fig. 5 Total pressure distribution inside the rotor cylinder (Pascal)

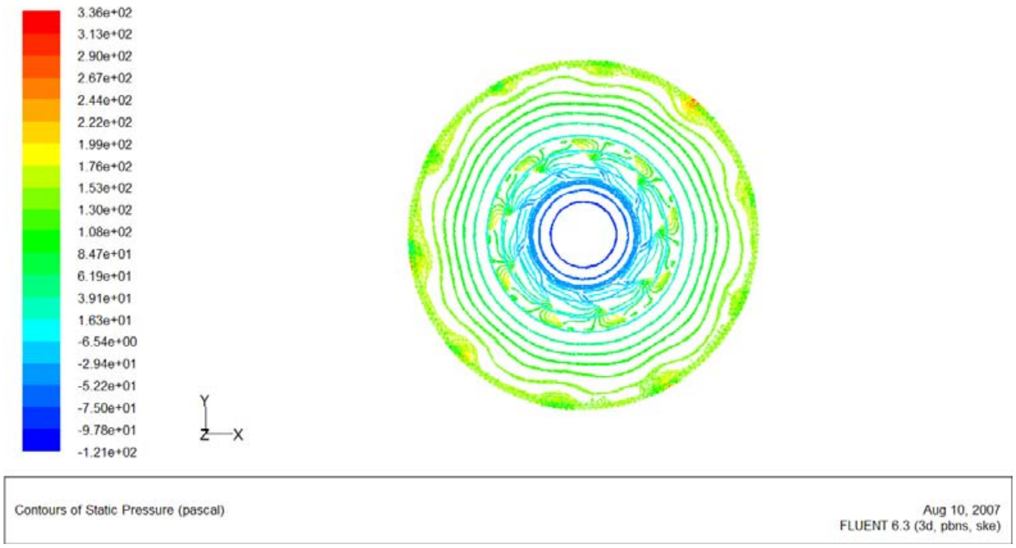
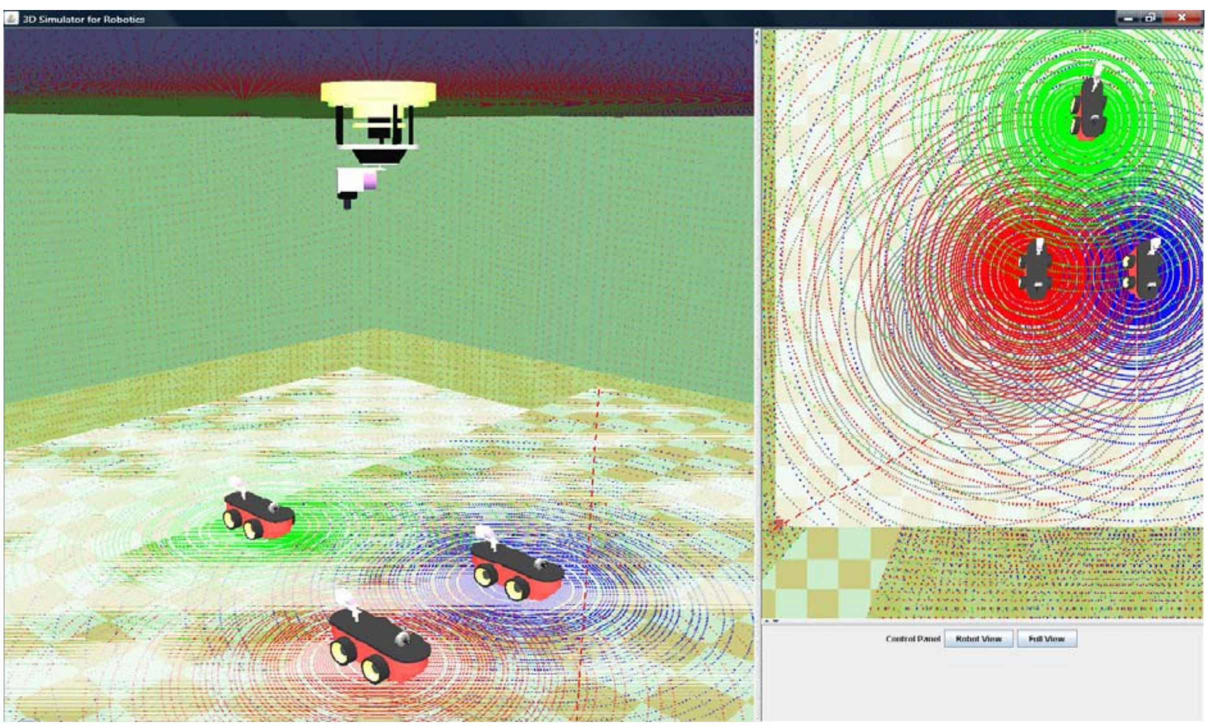


Fig. 6. Static Pressure distribution, rotor speed: 1200rpm, chamber size: scale 1, fully seal

C. Collaborative Localization and Mapping in 3D

We have developed an integrated approach for constructing a **complete 3D map** (i.e., a map showing most details of ceilings, ground and furniture top surfaces which normally cannot seen by ground robots in indoor environments) using multiple robots and multi-modal sensing in indoor environments. First, we have developed intra-localization methods among three ground robots and one City-Climber robot in constrained 3D space. The ground robots are equipped with panoramic or wide-angle-lens cameras, and mutually view each other and localize among themselves. We proposed a deterministic method and a probabilistic method which solved the perspective three points (P3P) camera pose estimation problem with unique solutions to determine the pose of the overhead camera installed on wall-climbing robot with respect to the ground robot. The deterministic method can generate the unique solution to P3P problem by moving the wall-climbing robot straight for two small steps. The probabilistic algorithm is inspired by Monte Carlo method and can continuously determine the wall-climbing robot's pose by moving along arbitrary trajectory. Based on the unique solutions to the P3P problem, we introduced an intra-robot localization method to determine the geometric relationship among the robot team with three ground robots and one wall-climbing robot at a stationary formation. Secondly, each robot is equipped with a rotary laser range sensor, which scans and produces 3D point cloud map from its own point of view. Finally, the four individual maps are integrated to construct a complete 3D map using the geometric information acquired by the intra-localization process. Compared with the traditional range fusion algorithms which use feature points or environment similarities for map integration and may require minutes to process, our method is easy to implement and can run in real time. The proposed 3D mapping approach is suitable for application sceneries when a group of robots (including wall-climbing robots) is deployed in a large building with a mission to construct a 3D map quickly. Figure 7 and 8 show the real experiment setup and 3D simulator respectively. Please see related publications [7. 10, 15] for details.

Fig. 7 Experimental settings for 3D map construction using 3 ground robots and a City-Climber robot



We have developed control algorithms for multi-robot coordination and swarming robots. In [4, 18], we presented a new kinematics model for the leader following based formation control of

multiple nonholonomic mobile robots using Cartesian coordinates. Based on the special feature of this new model, we utilize the idea of integrator backstepping to derive a globally stable controller. The new model and controller avoid the singularity problem inherent in polar coordinates representation and previously ignored by researchers. Simulation results verify the efficacy of presented new model and controller. In [5, 12, 13, 14, 17], we proposed several general decentralized controllers for the swarming robots to achieve a collective group behavior in both fixed topology and dynamic topology. We assume that during the process of swarming, each agent can sense and interact with its nearest neighbors while following certain path clues of the environment. By combining the ideas of virtual force and nearest neighborhood law, the controllers are proved to enable the velocity vectors of all agents to asymptotically converge to a common value. The advantage of the controller is that all necessary information can be locally sensed, therefore, communication link and issues about it (such as time delay) are avoided. The efficiency of the control algorithms has been verified by the simulation results.

E. Dynamic 3D Scene Modeling and Representation

We proposed a content-based 3D mosaic representation (CB3M) for long video sequences of 3D and dynamic scenes captured by a camera on a mobile platform [19-25]. The motion of the camera has a dominant direction of motion (as on an airplane or ground vehicle), but 6 DOF motion is allowed. In the first step, a pair of generalized parallel-perspective (pushbroom) stereo mosaics is generated that captured both the 3D and dynamic aspects of the scene under the camera coverage. A ray interpolation approach is used to generate seamless parallel-perspective stereo mosaics under obvious motion parallax of a translating camera. In the second step, a segmentation-based stereo matching algorithm is applied to extract parametric representation of the color, structure and motion of the dynamic and/or 3D objects in urban scenes where a lot of planar surfaces exist. In the algorithm, we use the fact that all the static objects obey the epipolar geometry, i.e. along the epipolar lines of pushbroom stereo. An independent moving object (moving on a road surface), on the other hand, either violates the epipolar geometry if the motion is not in the direction of sensor motion or exhibits unusual 3D structure – obviously hanging above the road or hiding below the road. The content-based 3D mosaic (CB3M) representation is a highly compressed visual representation for a very long video sequence of a dynamic 3D scene.

The 3D modeling and representation approach has been applied to wall-climbing robots. We have modified the content-based 3D representation for the use of 3D urban scene understanding for City-Climber navigation. Figure 9 shows an experimental result in finding all the planar surfaces of ground, walls, doors and other objects. Note that depth information is obtained for all the points (including those in textureless regions) in images. Further, the depth information is in the form of parametric representations of the planar surfaces that are ready for wall-climbing robot navigation. We are optimizing the code so that real-time performance can be achieved. We are continuing in algorithms that integrated multiple 3D planar reconstruction results to generate a more global and more accurate map for classifying surfaces for wall-climbing robots. A paper is in preparation for IROS 2009.

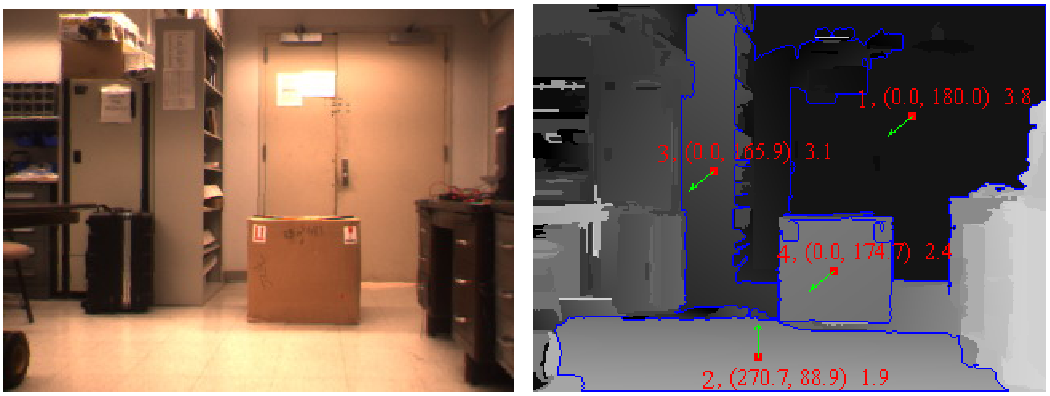


Fig. 9. The reference image of a stereo pair and its depth map The parameters of 4 patches are marked on the rendered depth map, each with its No, its boundary, its normal vector with two orientation angles (in degrees), and distance (in cm) from the reference camera to the center of each patch.

In addition, the parallel-perspective stereo model has also been used in another important robotic application: cargo inspection with a portable moving gamma-ray imaging system [24-26]. In [24], a linear pushbroom scanning model is built for such a commonly used gamma-ray or x-ray cargo inspection system. Three-dimensional (3D) measurements of the objects inside a cargo can be obtained by effectively constructing a pushbroom stereo system using two such scanning systems with different scanning angles. A simple but robust calibration method is proposed to find the important parameters of the linear pushbroom sensors. Then, a fast stereo matching algorithm is developed to obtain 3D measurements of the objects under inspection.

F. Fault-Tolerant Smart Resource Reconfiguration for Distributed Robotic Tasks

A team of multiple distributed robots can share information gathered by a variety of sensors and use this information to accomplish a cooperative task. To satisfy their objectives, distributed robots have to deal with two essential problems: coherent aggregation of information from multiple sensors and coordinated control of motor subtasks. We design a smart resource reconfiguration architecture that enables several robotic entities with different abilities to exchange information in a timely manner in order to achieve a common goal, say tracking of multiple objects in a indoor smart environment. The progress of the task may be interrupted by various run-time failures, including: hardware failure, inadequate sensor geometries, occlusion, and bandwidth limitations. We define a software construct called Fault Containment Unit (FCU) which enables run-time fault-tolerance by a combination of knowledge regarding the physical sensorimotor device, its use in coordinated sensing operations, and high-level process descriptions. We have demonstrated the utility of our architecture in a distributed vision task. Multiple cameras share the visual tracking signatures of the moving objects between them. The system can decide on the best set of cameras to observe objects of interest at any instant. Such a decision is influenced by the dynamics of the moving object, desired tracking accuracy etc**.** The work is summarized in our recent paper [27].

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REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

(1) List of papers submitted or published under ARO sponsorship **during this reporting period**. List the papers, including journal references, in the following categories:

(a) Manuscripts submitted, but not published

1. Peter Brass, A. Gasparri, Flavio Cabrera-Mora, Jizhong Xiao, “Multi-robot Tree and Graph Exploration”, 2009 IEEE International Conference on Robotics and Automation (ICRA’2009), to appear.
2. H. Tang and Z. Zhu, Content-Based 3D Mosaics for Representing Videos of Dynamic Urban Scenes, IEEE Transactions on Circuits and Systems for Video Technology, accepted, August 2008, to appear.

(b) Papers published in peer-reviewed journals

3. Z. Zhu, Mobile Sensors for Security and Surveillance, Journal of Applied Security Research, the Haworth Press, vol 4, no 1&2:79–100, January 2009 (invited paper).
4. D. R. Karuppiah, R. A. Grupen, Z. Zhu and A. R. Hanson, Automatic Resource Allocation in a Distributed Camera Network, Machine Vision and Applications, January 2009, Online First at http://dx.doi.org/10.1007/s00138-008-0182-7
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(c) Papers published in non-peer-reviewed journals or in conference proceedings

6. Yi Feng, Zhigang Zhu, Jizhong Xiao, “Self-localization of a Heterogeneous Multi-robot Team in Constrained 3D Space”, 2007 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS’2007), pp1343-1350, San Diego, Oct. 29~Nov. 2, 2007.
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10. Rex Wong, Sheng Hu, Flavio Cabrera-Mora, Jizhong Xiao and Jindong Tan, “A Distributed Algorithm for Mobile Robot Navigation and Mapping in Wireless Sensor Networks”, IEEE International Conference on Information and Automation (ICIA’2008), pp560~566, June 20~23, Hunan, China, 2008.
11. Xiaohai Li, Zhijun Cai and Jizhong Xiao, “Stable Swarming by Mutual Interactions of Attraction/Alignment/Repulsion: Fixed Topology”, the 17th World Congress of International Federation of Automatic Control (IFAC’08), pp5143-5148, Seoul, Korea, July 6~12, 2008.
12. Yi Sun, Jizhong Xiao, Xiaohai Li, and Flavio Cabrera-Mora, "Adaptive Source Localization Using Signal Strength by a Mobile Robot in Sensor Networks", IEEE Global Communications Conference, New Orleans, USA, Nov. 30~Dec. 4, 2008.
13. Xiaohai Li, Jizhong Xiao and Zhijun Cai, “Stable Swarming by Mutual Interactions of Attraction/Alignment/Repulsion”, 47th IEEE Conference on Decision and Control (CDC’2008), pp1036-1041, Cancun, Mexico, Dec. 9~11, 2008.
14. Ravi Kaushik, Yi Feng, William Morris, Jizhong Xiao, Zhigang Zhu, “3D Map Construction Using Heterogeneous Robots”, 10th International Conference on Control, Automation, Robotics and Vision (ICRACV’2008), pp1230-1235, Hanoi, Vietnam, Dec. 17~20, 2008.

(d) Papers presented at meetings, but not published in conference proceedings

(2) Demographic Data **for this Reporting Period**:

(a) Number of Manuscripts submitted during this reporting period:

14

(b) Number of Peer Reviewed Papers submitted during this reporting period:

14 (include journal submissions, book chapters, and peer reviewed conference publications)

(c) Number of Non-Peer Reviewed Papers submitted during this reporting period:

(d) Number of Presented but not Published Papers submitted during this reporting period:

(3) Demographic Data **for the life of this agreement**:

(a) Number of Scientists Supported by this agreement (decimals are allowed): 2 faculty members
(b) Number of Inventions resulting from this agreement: 1 patent filed
(c) Number of PhD(s) awarded as a result of this agreement: 0
(d) Number of Bachelor Degrees awarded as a result of this agreement

CCNY Robotics Lab and EE Dept. – 20 (EE students participating robotics capstone design projects)
CCNY Visual Computing Lab – 11 (4 ME students participating in ME/CS capstone design projects, 7 CS students in two multimodal sensing capstone design projects)

(e) Number of Patents Submitted as a result of this agreement

one (1) patent application filed

(f) Number of Patents Awarded as a result of this agreement; 0
(g) Number of Grad Students supported by this agreement: 7

CCNY Robotics Lab – Xiaohai Li, Angel Calle, Ravi Kaushik, Flavio Cabrera-Mora, and Yi Feng (co-supervised by Xiao and Zhu)
CCNY Visual Computing Lab – Tao Wang, Hao Tang, Yi Feng (co-supervised by Xiao and Zhu)

(h) Number of FTE Grad Students supported by this agreement: 0
(i) Number of Post Doctorates supported by this agreement: 0
(j) Number of FTE Post Doctorates supported by this agreement: 0
(k) Number of Faculty supported by this agreement: 2

CCNY Robotics Lab – Jizhong Xiao (PI)
CCNY Visual Computing Lab – Zhigang Zhu (Co-PI)

(l) Number of Other Staff supported by this agreement: 0
(m) Number of Undergrads supported by this agreement: 4, (Igor Labutov, William Morris, Wai Khoo, Tad Jordan)
(n) Number of Master Degrees awarded as a result of this agreement: 4
CCNY Robotics Lab – Angel Calle, Ravi Kaushik, Flavio Cabrera-Mora
CCNY Visual Computing Lab – Weihong Li (MS)

(4) Student Metrics for graduating undergraduates funded by this agreement:
(a) Number of undergraduates funded by your agreement during this reporting period.
4
(b) Number of undergraduate funded by your agreement, who graduated during this period.
0
(c) Number of undergraduates funded by your agreement, who graduated during this period with a degree in a science, mathematics, engineering, or technology field.
0
(d) Number of undergraduates funded by your agreement, who graduated during this period and will continue to pursue a graduate or Ph.D degree in a science, mathematics, engineering, or technology field.
0
(e) Number of undergraduates funded by your agreement, who graduated during this period and intend to work for the Defense Department.

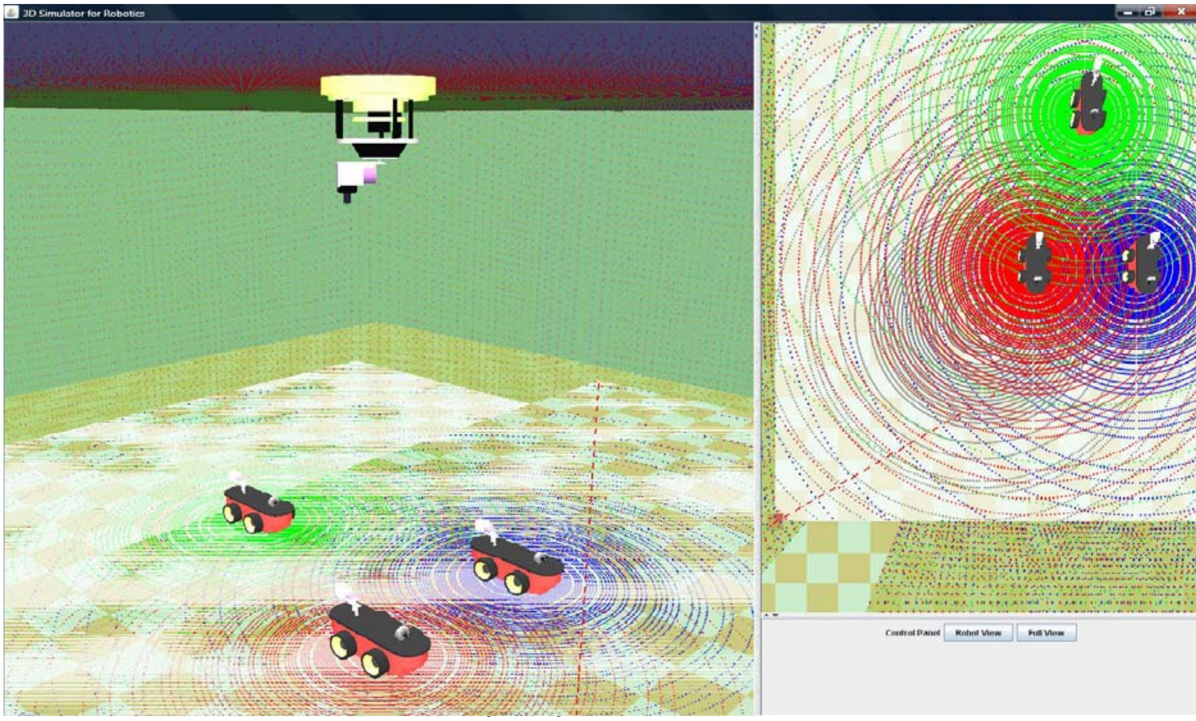
(f) Number of undergraduates graduating during this period, who achieved at least a 3.5 GPA based on a scale with a maximum of a 4.0 GPA. (Convert GPAs on any other scale to be an equivalent value on a 4.0 scale.)
4
(g) Number of undergraduates working on your agreement, who graduated during this period and were funded by a DoD funded Center of Excellence for Education, Research or Engineering.

(h) Number of undergraduates funded by your agreement, who graduated during this period and will receive a scholarship or fellowship for further studies in a science, mathematics, engineering or technology field.
2
(5) “Report of inventions” (by title only)
“Modular Wall Climbing Robots with Transition Capability”, Jizhong Xiao and Ali Sadegh, CUNY new technology disclosure approved, U.S. Patent Application Serial No. 11/400,654.

(6) “Scientific progress and accomplishments” (Description should include significant theoretical or experimental advances)

In the final reporting period, we conducted theoretical research on 3D map construction and laser data fusion problems. We also developed a 3D simulator and conducted real experiments to verify the theoretical results. We proposed an integrated approach for constructing a **complete 3D map** (i.e., a map showing most details of ceilings, ground and furniture top surfaces which normally cannot seen by ground robots in indoor environments) using multiple robots (ground robots and a wall-climbing robot) and multi-modal sensing (cameras, and laser range sensors). First, we proposed a probabilistic method which solved the perspective three points (P3P) problem with unique solutions to determine the pose of the overhead camera installed on wall-climbing robot. This method provides an alternative approach to tackle the P3P problem, which has been proved to be an under-determined problem since 1841. Second, based on the unique solutions to the P3P problem, we introduced an intra-robot localization method to determine the geometric relationship among a robot team with three ground robots and one wall-climbing robot at a stationary formation. Then, the rotary laser range sensors on the robots scan and produce 3D point cloud map from its own point of view. Finally, the four individual maps are integrated to construct a complete 3D map using the geometric information acquired by the intra-localization process. Compared with the traditional range fusion algorithms which use feature points or environment similarities for map integration and may require minutes to process, our method is easy to implement and can run in real time. The proposed 3D mapping approach is suitable for application scenarios when a group of robots (including wall-climbing robots) is deployed in a large building with a mission to construct a 3D map quickly. Figure 1 and 2 show the real experiment setup and 3D simulator respectively. (Please see the related publications.)

Fig. 1 Experimental settings for 3D map construction using 3 ground robots and a City-Climber robot



ght impact the development of products.

1. We have developed some variant wall-climbing robot prototypes for building inspection and window cleaning tasks.
2. We are negotiating with Hasbro Inc. for licensing the City-Climber technology in toy industry through the CUNY technology commercialization office.
3. A start-up company INNOVBOT LLC is initiated in New York state to further develop City-Climber technology for different applications and to seek SBRI funding for technology commercialization.